Photoproduction of $K\Sigma(1385)$ from the nucleon

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Abstract. The reactions of $K\Sigma(1385)$ photoproduction, i.e., $\gamma p \to K^+\Sigma^0(1385)$ and $\gamma n \to K^+\Sigma^-(1385)$, are investigated in the resonance energy region for studying the role of the nucleon and Δ resonances of masses around 2 GeV. The Lagrangians for describing the decays of these resonances into the $K\Sigma(1385)$ channel are constructed and the decay amplitudes are obtained, which allows us to determine the coupling constants using the predictions of quark models or the data listed by the Particle Data Group. The resulting cross sections are compared to the data from the Thomas Jefferson National Accelerator Facility and the SPring-8, which indicates nontrivial contributions from the two-star-rated resonances in the Particle Data Group as well as from some missing resonances predicted by a quark model.

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Production of strange particles from photon-nucleon scattering has been extensively studied in recent experiments at electron/photon accelerator facilities [1, 2, 3, 4]. However, most of the data accumulated by these experiments are for the reactions of $K\Lambda(1116)$ and $K\Sigma(1193)$ production, and the photoproduction of the spin-$3/2$ hyperons such as the reaction of $\gamma p \to K\Sigma(1385)$ is virtually unknown until the recent experiments at JLab [5] and at SPring-8 [6]. The Σ^* or $\Sigma(1385)$ is the lowest mass hyperon in the baryon decuplet, so the analysis of its production mechanism will be valuable for testing the flavor SU(3) symmetry when combined with the analyzed production mechanism of $\Delta(1232)$ resonance.

Furthermore, this reaction is expected to have a nontrivial role in searching for the so-called missing resonances. This is based on the observation that, although the cross section of $\Sigma(1385)$ photoproduction is smaller than that of $K\Lambda(1116)$ and $K\Sigma(1193)$ photoproduction, the suppression factor is not large, which means that this reaction may have nontrivial role in a full coupled channel calculation for identifying new resonances and/or extracting the properties of baryon resonances.[1] In fact, the quark model of Ref. [10] predicts that several missing and not-well-established non-strange baryon resonances have large partial decay widths into the $K\Sigma(1385)$ channel, while the couplings of most well-established resonances to this channel are small. Then we may have a chance to see the effects of such missing or yet-to-be-established resonances through the analysis of $K\Sigma(1385)$ photoproduction process.

The recent experiments for $K\Sigma(1385)$ photoproduction were reported in Refs. [5, 6], which present the cross sections and the beam asymmetry of this reaction.[2] Theoretical investigation of $K\Sigma(1385)$ photoproduction, however, is rare. (See, for example, Refs. [13, 14].) Here we present the theoretical model of Ref. [15] for the reaction mechanisms of $\Sigma(1385)$ production in the reaction of $\gamma p \to K^+\Sigma^0(1385)$, which is based on the preliminary data of the JLab [5]. We then discuss the application of this model to the physical quantities in the reaction of $\gamma n \to K^+\Sigma^-(1385)$, of which data were reported in Ref. [6].

Our model for $K\Sigma^*$ photoproduction is depicted in Fig. 1. This includes the t-channel K and K^* meson exchanges [Fig. 1(a)], s-channel non-strange baryon exchanges [Fig. 1(b)], and u-channel hyperon exchanges [Fig. 1(c)]. It also contains the generalized contact term [Fig. 1(d)] that is introduced to restore gauge invariance. For the effective Lagrangians to calculate the production amplitudes from the diagrams for the t-channel K exchange, s-channel nucleon term, u-channel $\Sigma(1385)$ term, and the contact term, we refer the reader to Ref. [15], where the details of the effective Lagrangians and the coupling constants are discussed. Instead, we here focus on the Lagrangians which require more rigorous and detailed studies.

The t-channel K^* exchange involves the $\gamma K K^*$ and $K^* N \Sigma^*$ interactions. The Lagrangian for the former interaction is well known and its coupling constant can be determined from the measured width of the $K^* \to K\gamma$ decay. However, the Lagrangian for the latter interaction, which describes the vertex of $\frac{3}{2} \to 1 + \frac{1}{2}$ with the numbers representing the

[1] Note that similar conclusions were drawn also for $K^*\Lambda$ and $K^*\Sigma$ photoproduction [5, 7, 8, 9].
[2] The earlier experimental data for $K\Sigma(1385)$ photoproduction obtained in 1960's can be found, e.g., in Refs. [11, 12].

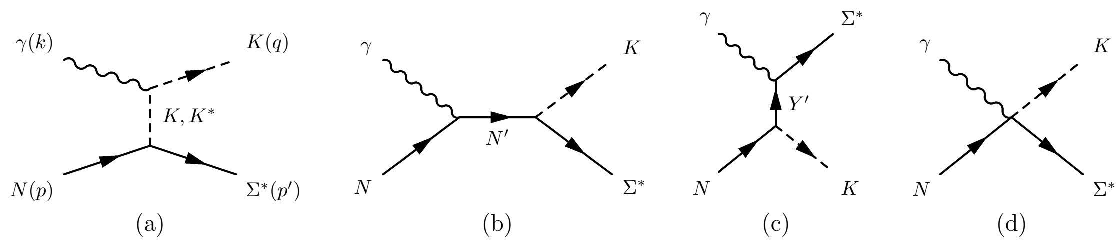

FIGURE 1. Feynman diagrams for $K\Sigma^*$ photoproduction. N' stands for the non-strange baryons and their resonances, while Y' the hyperons with strangeness -1 and their resonances. Diagram (d) includes the contact term of which form can be found in Ref. [15].

spin of the participating particles, has not been studied in detail. This interaction contains three terms in general, which can be written as

$$\mathscr{L}_{K^*N\Sigma^*} = \frac{ig_1}{2M_N}\overline{K}^{*\mu\nu}\overline{\boldsymbol{\Sigma}}^*_\mu\cdot\boldsymbol{\tau}\gamma_\nu\gamma_5 N + \frac{g_2}{(2M_N)^2}\overline{K}^{*\mu\nu}\overline{\boldsymbol{\Sigma}}^*_\mu\cdot\boldsymbol{\tau}\gamma_5\partial_\nu N - \frac{g_3}{(2M_N)^2}\partial_\nu\overline{K}^{*\mu\nu}\overline{\boldsymbol{\Sigma}}^*_\mu\cdot\boldsymbol{\tau}\gamma_5 N + \text{ H.c.}, \tag{1}$$

where $K^*_{\mu\nu} = \partial_\mu K^*_\nu - \partial_\nu K^*_\mu$. The coupling constants of this interaction is unknown and may be determined from the corresponding couplings of the $\rho N\Delta$ interaction if we invoke the SU(3) symmetry relation. However, even the couplings of the $\rho N\Delta$ interaction are poorly known and, in most analysis, only the g_1 term has been used [16, 17]. In this work, we fix the coupling g_1 of the $K^*N\Sigma^*$ interaction by using the SU(3) symmetry with that of the $\rho N\Delta$ interaction and treat g_2 and g_3 as free parameters. Fortunately, it turns out that in our case, the contribution from the K^* exchange is suppressed and the uncertainties of those couplings could be ignored. However, it would be worth while to analyze the data for estimating all three couplings of the $\rho N\Delta$ interaction.

For the u-channel diagrams, we consider the case with $Y' = \Lambda(1116)$ and $\Sigma(1385)$. The former is the lowest mass hyperon and the latter is required to fulfill the gauge invariance condition. Since one of the motivation of this study is to investigate the non-strange baryon resonances in the s-channel diagrams, we start with the most general expressions for the interactions of $RN\gamma$ and $RK\Sigma^*$, which read

$$\begin{aligned}
\mathscr{L}_{RN\gamma}(\tfrac{1}{2}^\pm) &= \frac{ef_1}{2M_N}\bar{N}\Gamma^{(\mp)}\sigma_{\mu\nu}\partial^\nu A^\mu R + \text{H.c.}, \\
\mathscr{L}_{RN\gamma}(\tfrac{3}{2}^\pm) &= -\frac{ief_1}{2M_N}\overline{N}\Gamma^{(\pm)}_\nu F^{\mu\nu}R_\mu - \frac{ef_2}{(2M_N)^2}\partial_\nu\bar{N}\Gamma^{(\pm)}F^{\mu\nu}R_\mu + \text{H.c.}, \\
\mathscr{L}_{RN\gamma}(\tfrac{5}{2}^\pm) &= \frac{ef_1}{(2M_N)^2}\bar{N}\Gamma^{(\mp)}_\nu\partial^\alpha F^{\mu\nu}R_{\mu\alpha} - \frac{ief_2}{(2M_N)^3}\partial_\nu\bar{N}\Gamma^{(\mp)}\partial^\alpha F^{\mu\nu}R_{\mu\alpha} + \text{H.c.},
\end{aligned} \tag{2}$$

and

$$\begin{aligned}
\mathscr{L}_{RK\Sigma^*}(\tfrac{1}{2}^\pm) &= \frac{h_1}{M_K}\partial_\mu K\bar{\Sigma}^{*\mu}\Gamma^{(\mp)}R + \text{H.c.}, \\
\mathscr{L}_{RK\Sigma^*}(\tfrac{3}{2}^\pm) &= \frac{h_1}{M_K}\partial^\alpha K\bar{\Sigma}^{*\mu}\Gamma^{(\pm)}_\alpha R_\mu + \frac{ih_2}{M_K^2}\partial^\mu\partial^\alpha K\bar{\Sigma}^*_\alpha\Gamma^{(\pm)}R_\mu + \text{H.c.}, \\
\mathscr{L}_{RK\Sigma^*}(\tfrac{5}{2}^\pm) &= \frac{ih_1}{M_K^2}\partial^\mu\partial^\beta K\bar{\Sigma}^{*\alpha}\Gamma^{(\mp)}_\mu R_{\alpha\beta} - \frac{h_2}{M_K^3}\partial^\mu\partial^\alpha\partial^\beta K\bar{\Sigma}^*_\mu\Gamma^{(\mp)}R_{\alpha\beta} + \text{H.c..}
\end{aligned} \tag{3}$$

where A_μ is the photon field ($F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$), and R, R_μ, and $R_{\mu\nu}$ are the fields for the spin-$1/2$, $3/2$, and $5/2$ resonances, respectively, with

$$\Gamma^{(\pm)}_\mu = \begin{pmatrix} \gamma_\mu\gamma_5 \\ \gamma_\mu \end{pmatrix}, \qquad \Gamma^{(\pm)} = \begin{pmatrix} \gamma_5 \\ \mathbf{1} \end{pmatrix}. \tag{4}$$

The coupling constants f_i and h_i can be related to the theoretical predictions on the partial decay amplitudes of the resonances. This has a great advantage compared with the use of partial decay widths as the relative phase of the

TABLE 1. Resonances and their coupling constants h_i and f_i based on the predictions of Ref. [10]. The coupling constants are calculated using the resonance masses of PDG.

Resonance	**PDG** [18]	h_1	h_2	f_1	f_2
$N\frac{1}{2}^-(1945)$	$S_{11}^*(2090)$	-0.98	—	0.055	—
$N\frac{3}{2}^-(1960)$	$D_{13}^{**}(2080)$	0.24	-0.54	-1.25	1.21
$N\frac{5}{2}^-(2095)$	$D_{15}^{**}(2200)$	0.29	-0.08	0.37	0.28
$\Delta\frac{3}{2}^-(2080)$	$D_{33}^*(1940)$	-0.68	1.00	0.39	-0.57
$\Delta\frac{5}{2}^+(1990)$	$F_{35}^{**}(2000)$	-0.87	0.11	-0.68	-0.062
$N\frac{3}{2}^-(2095)$		0.99	0.27	0.49	-0.83
$N\frac{5}{2}^+(1980)$		0.59	0.24	0.019	-0.13
$\Delta\frac{3}{2}^-(2145)$		0.25	0.46	0.11	-0.059

coupling constants can be fixed. The explicit formulas for this relation were derived in Ref. [15], and the couplings fixed by the quark model prediction of Refs. [10] are listed in Table 1.[3] In this work, only the resonances which are predicted to have large couplings to the $K\Sigma^*$ channel in the model of Ref. [10] are considered.

Presented in Fig. 2 is the result of the total cross section for the $\gamma p \to K^+\Sigma^0(1385)$ reaction, which indicates nontrivial contribution from the missing and/or not-well-established resonances in production mechanism of this reaction. In particular, we find that nontrivial contributions from the $\Delta(2000)F_{35}$, $\Delta(1940)D_{33}$, and $N(2080)D_{13}$, as well as from the missing resonance $N\frac{3}{2}^-(2095)$ are required to describe the observed data of Ref. [5].

The same model is then applied to the reaction of $\gamma n \to K^+\Sigma^-(1385)$ with the same resonances and keeping the isospin symmetry. The predictions of this model for differential cross sections and beam asymmetry are compared with the data obtained by the LEPS Collaboration [6] in Fig. 3. Considering that only a few resonances are included and no additional parameters are allowed, the description of this model for the differential cross sections is reasonable. However, the difficulty in explaining the beam asymmetry indicates that more sophisticated and detailed analyses of the data are highly required to understand the production mechanism and to pin down the role of each baryon resonance.

In summary, we have explored the reactions of $K\Sigma(1385)$ photoproduction from the proton and the neutron targets.

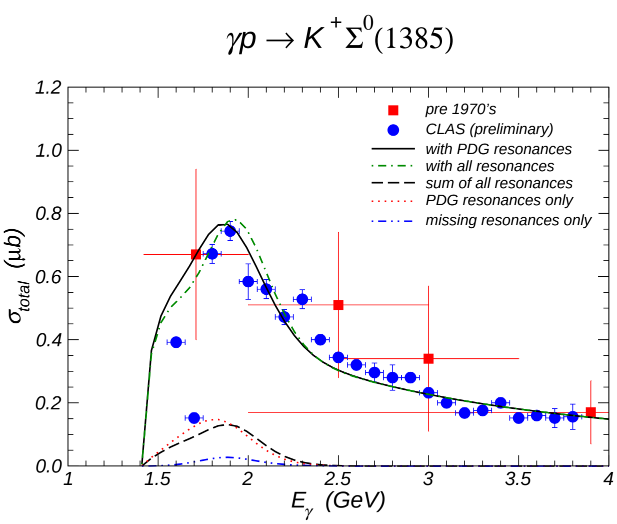

FIGURE 2. Total cross sections for the $\gamma p \to K^+\Sigma^0(1385)$ reaction with the resonance parameters listed in Table 1.

[3] The typographical errors committed in Ref. [15] are corrected here.

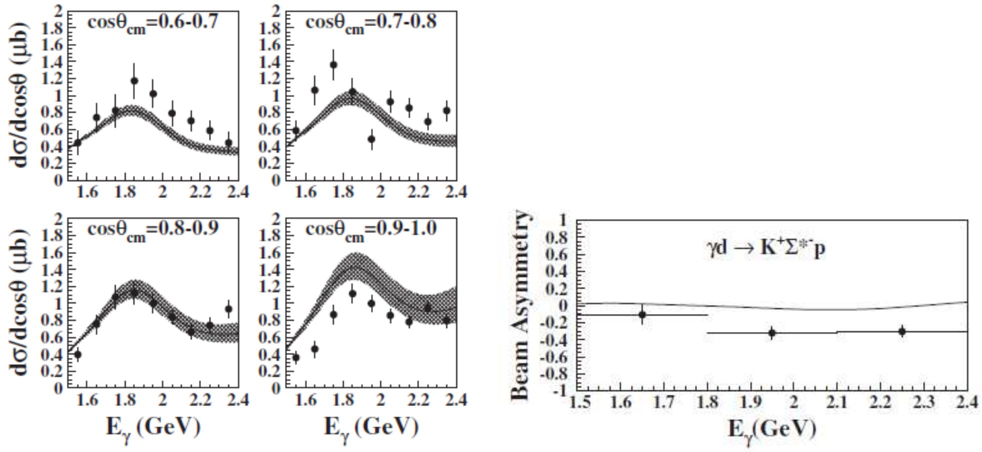

FIGURE 3. (Left panel) Differential cross sections for the $\gamma n \to K^+\Sigma^-(1385)$ reaction with the resonances listed in Table 1. (Right panel) Beam asymmetry of the same reaction.

We have constructed the Lagrangians for the interactions including baryon resonances up to spin-5/2, and the explicit formulas relating the coupling constants and the partial decay amplitudes were obtained. With the predictions of the quark model, we then calculate the cross sections and beam asymmetry of the reactions of $\gamma p \to K^+\Sigma^0(1385)$ and $\gamma n \to K^+\Sigma^-(1385)$, and the results are compared to the recent data measured by the CLAS and LEPS Collaborations. Our results for the cross sections manifestly indicate a nontrivial role of baryon resonances which are not-well-established or missing in the list of the Particle Data Group. However, the difficulty in explaining the measured beam asymmetry data for the $\gamma n \to K^+\Sigma^-(1385)$ reaction shows that much more detailed analyses are required to understand the production mechanisms of $\Sigma(1385)$.

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